A SEMI-ADAPTIVE APPROACH TO IN-FLIGHT MONITORING USING ACOUSTIC EMISSION

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INTRODUCTION

Acoustic emission (AE) is one of several promising non-destructive inspection (NDI) techniques for assessing defect growth in aircraft. Its potential for monitoring defects on a continuous basis, in situ, has stimulated various laboratories to carry out extensive research and application programmes in AE. Much of this work is applicable to structural testing of aircraft (1) and may later be applicable for use as part of a damage tolerance approach for aircraft stuctural management.

In any AE application, a major problem is to discriminate between AE from spurious sources and from (say) crack growth (1-5). Frequency discrimination and source location are common initial steps in AE source discrimination. Two distinct approaches have evolved for subsequent processing (6). The first approach, described variously as fundamental, deterministic or non-adaptive, involves developing quantitative relationships between defect parameters and AE (6, 7); the second, labelled as empirical, stochastic or adaptive, involves acquiring large quantities of data and seeking empirical correlations between defect types and AE data (6, 8, 9, 10, 11).

This paper briefly reviews existing procedures for distinguishing between AE sources in aircraft structures. Limitations in the applicability of frequency discrimination and source location techniques are addressed, and the failings of the fundamental and empirical approaches are shown. A semi-adaptive approach is proposed, which combines the results of research on AE sources, sensors and wave propagation (using calibration studies) to predict features of AE waveforms from crack growth in different locations in a structure. The semi-adaptive approach is applied to the processing and analysis of AE waveforms, detected during full-scale fatigue testing of a Mirage aircraft (5, 12, 13), to distinguish between spurious sources and AE from fatigue crack propagation in bolt holes in the aircraft's aluminium alloy wing-spar.

PROCESSING AND ANALYSIS OF AE DATA

Many AE sources are present in an aircraft during flight or fatigue testing. Hence, considerable signal processing and analysis are required if AE from fatigue crack propagation is to be distinguished from spurious AE sources.

Initial Treatment Of Extraneous Sources

AE from fatigue crack propagation will have frequency components up to many megahertz while vibration signals most often occur below 100 kHz. Thus, many of the latter signals can be removed by filtering. In addition, modern equipment is usually adequately protected against transient electromagnetic interference, which is usually at very high frequencies.

Source location systems are used to locate any AE sources within, and reject extraneous sources from outside, a region of interest. Differences in arrival times of elastic waves at an array of sensors are measured, a wave speed is assumed and algorithms are used to calculate the location of an AE source. Some location systems assign co-ordinates to the source while others assign it to a zone within the region of interest.

Source location is most readily achieved in simple structures where the mode of wave propagation is known (14, 15). However, problems can be expected in complex 3-D structures where wave propagation occurs as a complex combination of longitudinal, shear and Rayleigh waves. The type of wave detected by each sensor in the array will depend on the magnitude of the AE source, the relative locations of source and sensor, and the effects of boundaries on the presence of reflected or mode-converted waves. There will also be errors in the location of an internal source, of the order of the source depth (6). Clearly, an extensive sensor array, complicated algorithms and time-consuming computation are involved, if AE source location is to be achieved in an irregular 3-D structure.

Guard sensors are used in combination with a sensor array to minimize the effects of sources extraneous to a region of interest. Noise sources external to the array are identified and a guard is mounted between noise and array; AE events reaching the guard before the array are rejected. Alternatively, rejection is controlled by measuring differences in time-of-flight between guard and array sensors. The effectiveness of guard sensors depends on factors such as the wave speed assumed for calculation of time-of-flight, how many guard sensors are used and the activity of any extraneous sources. Our experience has shown that (i) highly active extraneous sources (which are often difficult to locate and identify) exist in aircraft applications, (ii) large numbers of guard sensors are needed to control noise sources, and (iii) assignment of a suitable wave speed in a complex component is difficult (5, 16) - additional AE signal processing will always be needed to distinguish between AE signals from different sources.

Limitations Of Fundamental Or Empirical Approaches

Three elements determine the characteristics of a detected AE signal: the source mechanism, the wave propagation path in the structure between source and sensor, and the sensor itself. In principle, if the effects of wave propagation and detection can be deconvoluted from the AE signal, the complete character (type, magnitude and time dependence) of an AE source can be obtained by measurements at six independent sensors (6).

This fundamental approach appears relatively straight-forward when an 'ideal' sensor (having a calibrated, wide-band response to a simple, physical parameter (6, 7, 17) is used for the AE measurements and the structure under investigation approximates to a half-space (or perhaps to a plate) (6). In a recent fundamental study of fatigue crack growth in a compact tension specimen of an aluminium alloy (18), multi-sensor measurement of directivity patterns of longitudinal waves allowed the discrimination of microcrack AE events associated with fatigue crack propagation and shear sources consistent with fretting between a loading pin and the specimen. However, this work is incomplete as a wider range of source types (particularly crack face rubbing) must be characterized. Even then, the measurement of features like directivity patterns will not be possible in complex structures.

A completely different approach ignores fundamental information and relies on adaptive learning principles. Empirical pattern recognition is applied to extract the features of possible AE sources from training sets of data (8-11). Source discrimination in an arbitrary data set is then undertaken using an appropriate combination of features to achieve an 'acceptable' error rate. Application of this statistical approach has not been successful because (i) well-defined training data sets from likely sources are not always available for analysis (e.g. AE from crack face rubbing), and (ii) propagation - and sensor-related rather than source-related features tend to be extracted from the training sets. Although it is possible to distinguish between vastly different sources such as crack-related AE and mechanical impacts, hydraulic noise and electrical transients, the differences between sources such as cracking and fretting are more subtle (10, 19). Thus a modified approach to data analysis in an arbitrary application is required.

Development Of A Semi-Adaptive Approach

The availability or usability of a priori information determines the degree of adaption that can be employed in signal processing problems (11). Clearly, a semi-adaptive approach is needed to distinguish between AE sources in complex aircraft structures, given limitations in both the availability and usability of information for a non-adaptive approach and the problems in implementing an adaptive approach.

The semi-adaptive approach we have developed is based on comparing features extracted from pattern recognition analysis (5, 19) of AE waveforms from an aircraft, with features predicted for possible sources. These features have been identified as a result of our research on AE sensors, wave propagation (modelled in irregular structures using calibration studies) and AE sources during fatigue crack propagation in aircraft aluminium alloys.

AE sensors. Our research programme has highlighted the need for careful selection of sensors so that sensor characteristics do not dominate pattern recognition features extracted from AE waveforms. A sensor with small aperture and wide-band response is important for pattern recognition, while characteristics such as high sensitivity, ease of coupling and robustness are always useful (17).

Calibration studies. Calibration studies have been used extensively in the determination of AE sensor characteristics and in some deconvolution studies to yield source characteristics (6, 7) but their use in pattern recognition analysis has been neglected. A feature of our semi-adaptive approach is the use of calibration measurements, undertaken using a simulated AE source, to predict features of an AE source appropriate to different combinations of test-piece, sensor and source location (where accessible). Propagation features are also obtained, to discriminate between subtly different sources (like bolt fretting and fatigue crack propagation), when they occur at different locations in a structure. We have found the fracture of pencil lead (7) to be a convenient, inexpensive and reproducible source for calibration studies in the laboratory and field (16, 19).

AE sources. Our AE studies of aircraft aluminium alloys indicate that inclusion fracture in the crack tip plastic zone is a likely AE source during fatigue crack propagation (5). The risetime, duration, autocorrelation characteristics and the distribution of load cycle positions of AE signals have been identified as useful pattern recognition features. Inclusion fracture is expected to occur at the peak of a load cycle during fatigue crack propagation, and may also occur on a positive load gradient (depending on loading history). A variability in AE activity from cycle to cycle is also expected, related to any inhomogeneity in the size and spatial distribution of the inclusions.

The results of other researchers (see below) suggest that other possible sources could occur at a range of different load cycle positions, depending on factors like the loading conditions used (load limits, non-axiality in load application etc), the specimen configuration and microstructural considerations. For example, AE from fretting of a bolt in a hole was observed on negative load gradients for fixed load limit cycling of bolted plates (10) and at other load cycle positions for misaligned specimens. AE from crack face rubbing has usually been observed on positive load gradients, below the mean load (20 - 22), being repetitive for many hundreds of cycles. Results of a recent study (23) suggest that AE from crack face rubbing could also occur at the peak of a load cycle under certain experimental conditions. However, the results of this study were difficult to evaluate, because of the possible effects of an inhomogeneous size distribution of inclusions on the AE detected during a limited number of load cycles.

AE MONITORING OF MIRAGE

Background Information

Some bolt and rivet holes situated in the bottom flange of the aluminium alloy wing-spar of a Mirage aircraft were known to be fatigue critical. An NDI technique was sought to enable continuous monitoring of these holes to be conducted. Interference fit bolts were used on the forward side of the flange; close tolerance bolts and rivets were used on the rear side of the flange, the five bolt holes closest to the mainframe having interference fit stainless steel bush inserts (24). Thus, AE appeared a promising technique for continuous monitoring of any defects in the wing-spar, because the application of more conventional NDI techniques would have required factory disassembly of the wing.

Aeronautical Research Laboratories (ARL) contracted Battelle Pacific Northwest Laboratories to install AE equipment on a full-scale fatigue test of the Mirage aircraft, conducted at a Swiss aircraft factory (5, 12). Two wings were monitored by AE, wing RH79 and wing RH56 which replaced wing RH79 (5).

Battelle mounted a six-sensor array on the lower surface of the bottom flange of wing RH56, for use in the time-of-flight source location of AE events. Two of the sensors were used to divide the spar into zones along the spar axis, while the four other sensors were used to distinguish between the forward and rear sides of the lower flange. Rayleigh wave detection was assumed, and AE events were either located into one of sixteen zones (labelled 4 to 19) or discarded (Fig 1).

The sixteen zones defined by time-of-flight criteria extended beyond the bottom flange of the wing-spar to surrounding regions (e.g. parts of the wing-skins and top flange of the spar). Nine guard sensors were used to minimize the likelihood of detecting AE events from these regions. Three guard sensors were coupled to a repair patch on the cracked rear wing-skin (Fig 2), four on the web between the top and bottom flanges and two on the lower surface of the bottom flange of the spar (Fig 2).

The guard and array sensors were made by Battelle especially for AE source location and comprised in essence a 1.7 mm radius air-backed disc. A similar type of sensor (located at W (Fig. 2)) was installed by Battelle for collection of waveform data but was rarely used. Amplified AE signals were digitized in a Biomation 1010 transient recorder with a capacity of 4096 10-bit words and sample interval set at 0.1 μs. Each digitized waveform was recorded on 9-track magnetic tape. The number of the zone in which the event was located and time in seconds relative to the start of the test were also recorded for each AE event.

Experimental Conditions for Semi-Adaptive Approach

Carefully designed AE experiments were undertaken on wing RH56 at the Swiss aircraft factory in August 1984 to allow application of the semi-adaptive approach to AE waveform processing and analysis (16). The existing data acquisition system was modified as follows. Valpey Fisher pinducers, wide-band sensors comprising a thin piezoelectric disc and delay-line matched backing, were used for waveform collection at either W1 or A1 (Fig 2). (The pinducers were particularly suited to pattern recognition measurements (17)). Information on the load cycle position of AE events was obtained by recording data from four strain gauges mounted along the length of the spar.

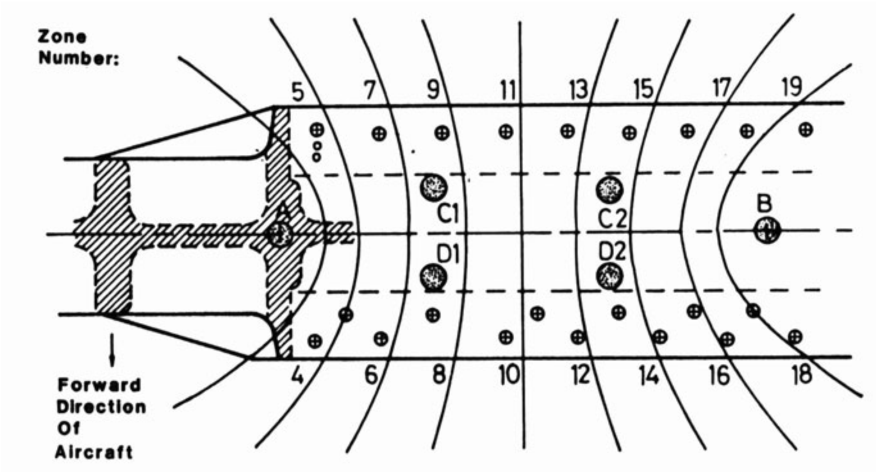

Fig. 1 Lower surface of bottom flange of Mirage wing RH56 showing
(i) AE sensor array (A, B, C1, C2, D1 and D2) used for source location,
(ii) ⊕ bolt holes and ∘ rivet holes,
(iii) the zones numbered 4 to 19.

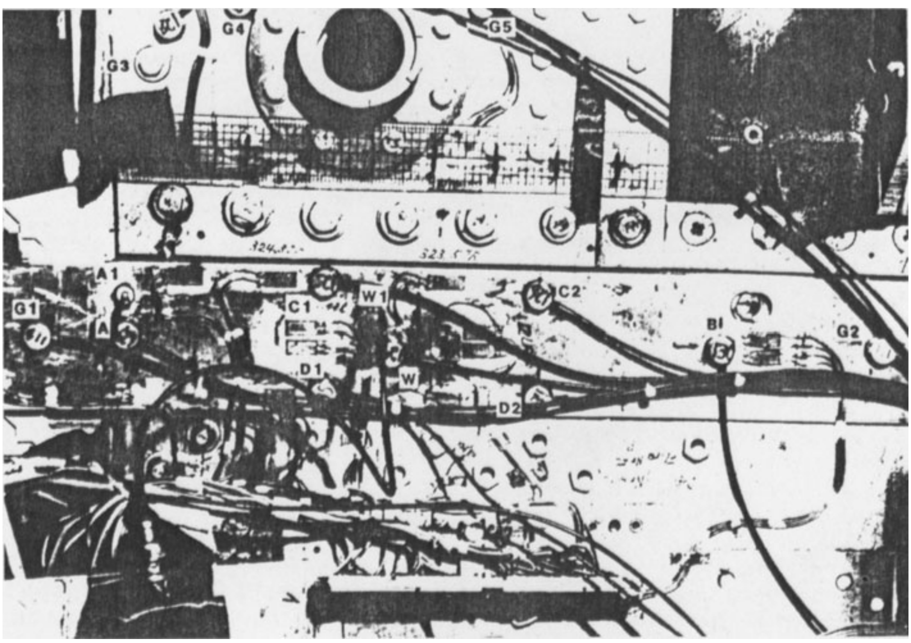

Fig. 2 Location of AE sensors on the lower surface of Mirage wing RH56: AE sensor array (A, B, C1, C2, D1, D2), waveform sensors W, W1 and A1, guard sensors G1 and G2 on the bottom flange of the wing-spar, and guard sensors G3, G4, and G5 on a patch on the wing-skin.

Calibration measurements were also undertaken on wing RH56, using fracture of a 2H 0.3 mm Pentel lead as a simulated source. The pinducers were characterized in situ, propagation features were determined for waves generated at the various bolt/rivet holes and propagating to the waveform sensors at AI and WI, and the effectiveness of the zone location system was assessed (16).

The pencil lead source was used in supplementary calibration studies at ARL, to determine propagation characteristics for AE generated at a single bolt hole in a thick cylinder and at bolt and rivet holes in a Mirage wing-spar without wing-skins or bolts/rivets.

Implementation of Semi-Adaptive Approach

The semi-adaptive approach was applied to the processing and analysis of the specialist AE waveforms from the Mirage full-scale fatigue test. Some examples of its use (viz. for the elimination of extraneous sources and the detection of fatigue crack propagation) will now be given, emphasis being placed on evaluation of waveforms assigned to zones 10 and 11. However, the procedure is representative of that involved for any monitored zone (19).

Elimination of Sources Extraneous to the Bottom Flange. Results from our calibration studies (see earlier) were used to define risetime/autocorrelation function criteria for AE waveforms from the zones in the bottom flange of the wing-spar. A waveform was rejected, as originating from outside the region of interest in the bottom flange, if its risetime was greater than 100 μs or if the first minimum in its autocorrelation function occurred at a lag of greater than 21. 77% of the waveforms in zone 10 were rejected but only 25% of the waveforms in zone 11.

The guard system was clearly satisfactory for zone 11, but allowed a significant number of extraneous sources to be located in zone 10 (probably because signals from a fairing attachment from the main-frame to the nearby wing-skin were not guarded out).

Detection of the AE from fatigue crack propagation. AE waveforms were identified as originating from inclusion fracture in the crack tip plastic zone during fatigue crack propagation, provided that the following three requirements were satisfied: (i) the waveforms occurred intermittently at the peak of a load cycle or on a positive load gradient, (ii) the waveform features lay within the range predicted by calibration studies, (iii) such features were not obtained for waveforms detected elsewhere on the load cycle.

AE waveforms satisfying all the above criteria, were assigned by the location system to zone 11 at both waveform sensor locations (A_I and W_I). Furthermore, these events were not repetitive, as would be expected for AE from crack face rubbing, but occurred infrequently, in keeping with the expected crack propagation rates (25). (Risetime characteristics of a sample of AE waveforms detected at AI and assigned to zone 11 are shown in Fig 3, while a typical test flight used in the Mirage fatigue test, showing the occurrence of a peak load, zone 11 event, is illustrated in Fig 4).

No AE waveforms with characteristics corresponding to inclusion fracture were assigned to zone 10.

Incorrect Assignment of Zone 11 Events. It was found from the calibration measurements that the characteristics of the peak load signals assigned to zone 11 corresponded to AE from fatigue crack propagation in the wing-spar at the zone 9 bushed bolt hole. In addition different features were obtained for calibration measurements undertaken at other likely sources of cracking and fretting for which AE could possibly be assigned to zone 11. For example, signal risetimes detected at AI for the pencil lead source applied to the edge of the bolt in the zone 11 bushed hole corresponded to those obtained for decreasing load gradients and load minima during fatigue testing (Fig 3). Calculations based on the spar geometry confirmed

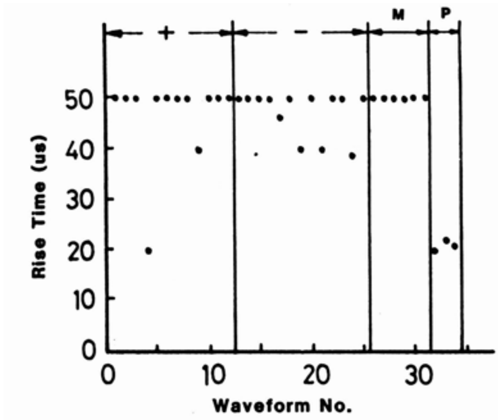

Fig. 3 Risetimes and load cycle position (+ positive load gradient, - negative load gradient, M load minimum, P load peak) are given for a sample set of waveforms assigned to zone 11. The waveform set was obtained during 35 test flights with the waveform sensor at A1 and an amplifier gain of 60dB(16), and had been subjected to preliminary processing to reject AE from extraneous sources. Note that all P load signals have a short rise-time, that all M or - load signals have a long risetime and that an occasional + load signal has a short risetime.

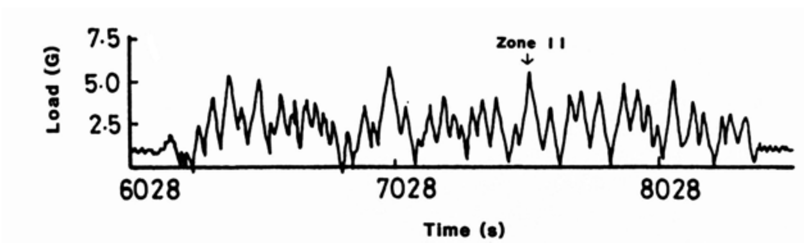

Fig. 4 A typical test flight in the Mirage fatigue test showing a peak load AE event (assigned to zone 11) which satisfied the criteria for inclusion fracture AE. (Only one such event occurred on the test flight despite the occurrence of several isolated peak loads).

that zone 9 events were assigned to zone 11 when first-arrival longitudinal rather than Rayleigh waves, were of sufficient amplitude to be detected by the array sensors A and B.

Confirmation of AE predictions. Metallography following completion of the full-scale testing of Mirage wing RH56 showed that several large cracks had propagated in the wing-spar at the zone 9 bolt hole during the fatigue test. (The largest crack had a depth of 6 mm.) No significant cracks (larger than about 0.5 mm in depth) were found in the zone 11 bolt hole or in the bolt holes which could have contributed to zone 10 emission. Thus the detection of inclusion fracture waveforms from zone 9 (incorrectly assigned to zone 11) and their absence in zone 10 is explained.

CONCLUSIONS AND FUTURE WORK

A powerful range of signal processing and analysis procedures are now available to distinguish between different AE sources. Sensor arrays and guard sensors can be used to eliminate many extraneous sources and to obtain a preliminary estimate of AE source location. Fundamental characteristics of AE sources can be obtained in simple structures. In addition, the semi-adaptive approach we have developed is applicable in more complex structures such as aircraft - in the Mirage application, this material/ science-based approach was successfully used to distinguish between AE from fatigue crack propagation and other AE sources detected during the full-scale fatigue test.

Further research on AE sources and sensors would allow a reduction in the degree of adaptation which was required in the Mirage analysis and would also facilitate future in-flight AE monitoring.

AE sensors. Suitable AE sensors now exist for short term AE monitoring - the pinducer was successfully utilized in the semi-adaptive approach developed for the Mirage analysis, while the NBS conical sensor (26) was recently used for quantitative AE measurements (18). Unfortunately neither of these sensors is easily coupled to a structure (see Fig. 2 for the pinducer), and the present NBS design is not robust. Hence long-term (or in-flight) continuous AE monitoring would require development of a modified sensor design.

Amplitude of AE signals. In principle, signal amplitude appears a useful feature for distinguishing between different AE sources. For example, in a recent study of 7050 aluminium alloy (21) the signal amplitudes associated with crack face rubbing extended to much higher levels than those associated with peak load crack propagation. However, recent theoretical results (27) suggest that the presence of a macrocrack significantly amplifies the amplitude of AE from a microcrack, i.e. the amplitude of AE from inclusion fracture in the crack tip plastic zone will depend on the relative sizes of the inclusion and the crack and their separation distance. Additional studies are required to clarify these effects, particularly for quantitative AE measurements.

Other source-related features. Further studies on the load cycle dependence of different AE sources are needed. The approach used in this paper was based on extending results from a few studies carried out during simple load cycling, but the load cycle occurrence of AE events during random load cycling needs to be rigorously investigated before it can be applied with complete confidence to the discrimination of different AE sources.

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REFERENCES

1. I.G. Scott, The status of in-flight monitoring using acoustic emission, presented at the N.Z. NDTA 10th annual Symposium, Wellington, (August 1986)
2. S.L. McBride and J.W. Maclachlan, J. Acoustic Emission 3, 1 (1984).
3. C.R. Horak and A.F. Weyhreter, Materials Evaln. 35 (5), 59 (1977).
4. W.M. Pless, C.D. Bailey and J.M. Hamilton, Materials Evaln. 36(4), 41 (1978).
5. C.M. Scala, R.A. Coyle and S.J. Bowles, An analysis of acoustic emission detected during fatigue testing of an aircraft, in: "Review of Progress in Quantitative Nondestructive Evaluation," Ed. D.O. Thompson and D.E. Chimenti, Vol. 4B, 709 Plenum Publishing Co., New York (1985).
6. C.B. Scruby, Quantitative acoustic emission techniques, in: "Research techniques in nondestructive testing," Ed. R.S. Sharpe, Vol. VIII, 141 Academic Press Inc., London (1985).

7. N.N. Hsu and S.C. Hardy, Experiments in acoustic emission waveform analysis for characterization of AE sources, sensors and structures, in: "Elastic waves and non-destructive testing of Materials," Ed. Y.H. Pao, AMD 29, 85 (1978).
8. D.R. Hay, R.W.Y. Chan, D. Sharp and K.J. Siddiqui, J. Acoustic Emission 3, 118 (1984).
9. P.H. Hutton, D.K. Lemon, R.B. Melton and P.G. Doctor, Develop in-flight acoustic emission monitoring of aircraft to detect fatigue cracks, in: Review of Progress in Quantitative Nondestructive Evaluation," Ed. D.O. Thompson and D.E. Chimenti, Vol. 1, 459 Plenum Publishing Co., New York (1982).
10. L.J. Graham and R.K. Elsley, J. Acoustic Emission 2, 47 (1983).
11. J.M. Richardson, R.K. Elsley and L.J. Graham, Pattern Recognition Letters 2, 387 (1984).
12. I.G. Scott, Monitoring crack growth during fatigue testing of aircraft by means of acoustic emission, in :"Proc. 4th Pan Pacific Conf. on Nondestructive Testing," Paper AE4, Sydney (1983).
13. C.M. Scala and R.A. Coyle, AE waveforms detected during fatigue testing of a Mirage aircraft (in preparation, 1986).
14. C.B. Scruby, J. Acoustic Emission 4, 9 (1985).
15. H.J. Rindorf, Bruel and Kjaer Technical Review 2 (1981).
16. C.M. Scala, Report on an overseas visit, Materials Tech. Memo 388, Aeronautical Research Labs., Melbourne (1984).
17. C.M. Scala, J. Acoustic Emission 2, 275 (1983).
18. C.B. Scruby, G.R. Baldwin and K.A. Stacey, Int. J. Fract. 28, 201 (1985).
19. C.M. Scala and R.A. Coyle, NDT International 16, 339 (1983).
20. T.C. Lindley, I.G. Palmer and C.E. Richards, Mater. Sci. Engng. 32, 1 (1978).
21. C.J. Kim and J. Weertman, Crack extension acoustic emission during fatigue crack growth, in : "Microstructural characterization of materials by non-microscopical techniques," Ed. N. Hessel Anderson et al., 349, RISØ (1984).
22. T. Ohira, T. Kishi and R. Horiuchi, Acoustic emission analysis of fatigue crack propagation in 7049 Al-Zn-Mg, Proc. Acoustic Emission Conf., Bad Nauheim, 241 (1980).
23. G. Weatherly, J.M. Titchmarsh and C.B. Scruby, Mater. Sci. and Technol. 2, 374 (1986).
24. J.Y. Mann, A.S. Machin and W.F. Lupson, Improving the fatigue life of the Mirage 1110 wing main spar, Structures Report 398, Aeronautical Research Labs., Melbourne (1984).
25. N.T. Goldsmith, Private Communication, Aeronautical Research Labs, (1985).
26. T.M. Proctor, J. Acoustic Emission 1, 173 (1982)
27. J.D. Achenbach, K.I. Hirashima and K.I. Ohno, J. Sound and Vibration 89, 529 (1983).